Comprehensive Basin Analysis and Petroleum Potential Evaluation of Ayoluengo Oil Field, Basque-Cantabrian Basin, Spain

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

This study presents a comprehensive basin analysis and petroleum potential evaluation of the Ayoluengo oil field in the Basque-Cantabrian Basin, Spain. Using an integrated approach combining geological, geophysical, and geochemical data, we analyzed the basin's evolution and petroleum system elements. The dataset included 2D and 3D seismic data, well logs, formation

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tops, and geophysical maps. Our analysis revealed a complex structural framework characterized by salt diapirism and halokinetic structures. Well log interpretation and sequence stratigraphic analysis identified two genetic sequences with associated systems tracts. Four reservoir units were mapped, with the main structural traps related to salt diapirs. Seismic facies analysis highlighted high-amplitude convergent (CBH) and high- and low-amplitude convergent (CBHL) facies as the most promising for reservoir quality. The study identified one play (Jurassic) and two prospects: Lias Limestone (80% geologic chance of success) and Carniolas Dolomite (85% geologic chance of success). Volumetric calculations estimate significant hydrocarbon potential, with STOIIP (Stock Tank Oil Initially In Place) ranging from 3.4 to 4.2 x 10^16 barrels for the Lias Limestone reservoir and 1.26 to 1.56 x 10^16 barrels for the Carniolas Dolomite reservoir.

1. INTRODUCTION

The Basque-Cantabrian Basin, located in northern Spain, has been a focal point of hydrocarbon exploration and production since the discovery of the Ayoluengo oil field in 1964 [1]. As the only onshore oil field in Spain, Ayoluengo has played a significant role in understanding this complex geological region's petroleum system and basin evolution. This study aims to conduct a comprehensive basin analysis and evaluate the Ayoluengo oil field's petroleum potential within the Basque-Cantabrian Basin's broader context. The Basque-Cantabrian Basin formed due to Mesozoic rifting and subsequent Alpine compression, creating a complex tectonic and stratigraphic framework [2]. The basin's evolution has led to the development of various source rocks, reservoirs, and trapping mechanisms, making it an intriguing subject for petroleum geologists and researchers alike. The Ayoluengo field, situated in the southwestern part of the basin, has produced over 17 million barrels of oil since its discovery [3]. Despite its relatively modest production, the field provides valuable insights into the basin's petroleum system and offers potential analogs for future regional exploration targets. This research will focus on integrating geological, geophysical, and geochemical data to reconstruct the basin's evolution, identify key elements of the petroleum system, and assess the remaining hydrocarbon potential of the Ayoluengo field and surrounding areas. By combining traditional basin analysis techniques with modern analytical methods, this study aims to contribute to understanding the Basque-Cantabrian Basin's hydrocarbon resources and guide future exploration efforts in this geologically complex region.
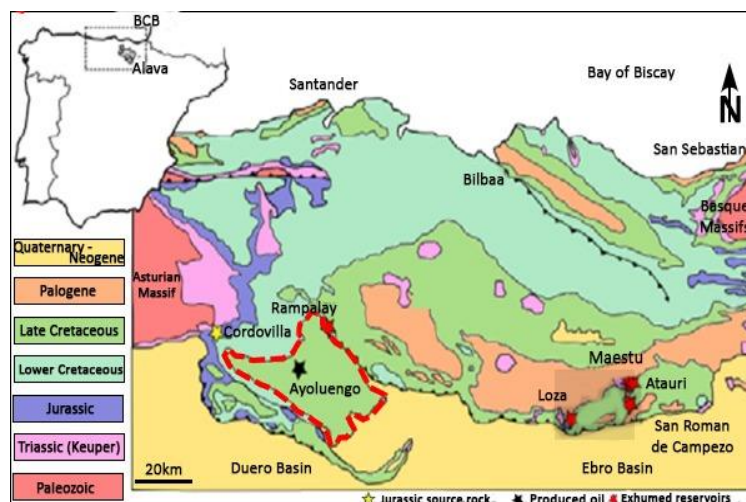

Fig. 1. Location map showing the regional setting of the Ayoluengo oil field in the Basque-Cantabrian basin, Spain, and the Basin Extent (Marin et al., 2012)

2. GEOLOGY AND STRUCTURAL SETTING

2.1 Basque-Cantabrian Basin

The Ayoluengo oil field is located within the Basque-Cantabrian Basin, a significant geological province situated in northern Spain. This basin is renowned for its complex geological history and structure.

2.2 Formation and Evolution

Rift System: The Basque-Cantabrian Basin originated during the Mesozoic era as part of the North Atlantic Bay of Biscay rift system. This rifting event resulted in the initial subsidence and formation of the basin, characterized by extensional tectonics.

Alpine Compression: The basin's geological history was profoundly influenced by Alpine compression during the Cenozoic era. This tectonic event led to significant structural modifications, including the formation of folds and thrusts. The compression associated with the Pyrenean orogeny is a key factor in the current geological configuration of the basin [4].

2.3 Stratigraphy

Paleozoic Basement: The basement of the basin is composed of Paleozoic rocks, which provide a stable foundation for the overlying sedimentary sequences.

Sedimentary Fill: Overlying the Paleozoic basement is a thick sequence of sedimentary rocks deposited through various geological periods:

Triassic Evaporites: These include thick layers of evaporitic deposits such as salt and gypsum, which are crucial in the basin's structural and hydrocarbon trapping mechanisms.

Jurassic Carbonates: During the Jurassic period, the basin experienced the deposition of extensive carbonate platforms, which are important for reservoir potential.

Cretaceous to Paleogene Deposits: This interval features a mix of clastic and carbonate sediments, reflecting changing depositional environments and contributing to the basin's overall complexity [5].

2.4 Structural Geology

2.4.1 Folding and thrusting

E-W Trending Structures: The basin's structure is dominated by east-west (E-W) trending folds and thrusts, which resulted from the compressional forces of the Pyrenean orogeny. These structures have played a critical role in shaping the basin's current geological framework [6].

Anticlinal Structures: The Ayoluengo oil field is situated on an anticline, a prominent fold structure created during the compressional event. This anticline serves as a key feature for hydrocarbon accumulation, as it provides structural traps for hydrocarbons.

2.4.2 Salt tectonics

Triassic Evaporites: The presence of Triassic evaporites, including salt, has significantly influenced the basin's structural evolution. Salt tectonics, including diapirism and halokinesis, have led to the formation of various structural and stratigraphic traps.

Diapirism and Halokinesis: Salt diapirs and associated halokinetic movements have created complex subsurface structures, including salt-cored anticlines and salt-induced folds. These features are critical for hydrocarbon trapping and migration, as they can act as both traps and barriers for hydrocarbons [7].

2.5 Petroleum System

2.5.1 Reservoir rocks

Lower Cretaceous Sandstones: The primary reservoir rocks in the Ayoluengo oil field are sandstones from the Lower Cretaceous Wealden facies. These sandstones were deposited in fluvial and deltaic environments, providing significant reservoir potential due to their porosity and permeability.

Interbedded Shales and Siltstones: These shales and siltstones serve as seals, preventing the upward migration of hydrocarbons and contributing to the field's overall reservoir capacity.

2.5.2 Source rocks

Jurassic Marine Shales: The source rocks for the Ayoluengo oil are primarily organic-rich

marine shales from the Jurassic period. These shales are crucial for hydrocarbon generation due to their high organic content and thermal maturity [8].

2.6 Implications for Hydrocarbon Exploration

Structural Complexity: The structural features of the basin, including salt tectonics and folding, have created a variety of potential traps and migration pathways for hydrocarbons. Understanding these structures is essential for effective exploration and development.

Reservoir and Seal Identification: Accurate identification and characterization of reservoirs and seals are critical for evaluating the hydrocarbon potential of the Ayoluengo oil field. The integration of stratigraphic and structural data will enhance the understanding of hydrocarbon accumulation and improve exploration strategies.

3. METHODOLOGY

1. Data Collection and Integration

This study utilized a comprehensive dataset to facilitate an in-depth analysis of the Ayoluengo oil field. The components of the dataset included:

- **Seismic Data:** A total of 203 2D seismic lines were analysed, complemented by 3D seismic data to achieve detailed subsurface imaging and interpretation across various scales (Yilmaz, 2001).
- **Well Data:** Data from eight wells were included, each offering complete well log suites, such as gamma ray, resistivity, and sonic velocities. Furthermore, check-shot surveys for four of these wells established critical time-depth relationships necessary for accurate depth conversion [9].
- **Formation Tops:** Formation tops for four wells were utilized to correlate geological layers and construct a stratigraphic framework (Tavakoli et al., 2015).
- **Auxiliary Data:** Additional geomagnetic data, gravity maps, surface geological maps, and geopolitical and geological posters provided essential context and insights into the regional geology (Telford et al., 1990).

2. Workflow and Methodology

The analysis was conducted through several systematic stages:

a. Basin Analysis

- **Tectonic Framework Study:** A comprehensive examination of the basin's structural features, including fault systems and deformation history, was conducted to evaluate their effects on sedimentary fill and petroleum potential (Sclater & Francheteau, 1970).
- **Paleogeographic Reconstruction:** A historical reconstruction of the basin's paleogeography was performed to infer past depositional environments and sedimentary processes [10].

b. Petroleum System Analysis

- **Source Rock Evaluation:** The study identified and assessed potential source rocks based on their maturity and kerogen type to evaluate hydrocarbon generation potential [11].
- **Migration Pathways:** Potential pathways for hydrocarbon migration were analyzed, considering both primary migration from source rocks and secondary migration within reservoirs [12].
- **Reservoir Rocks:** The quality of reservoir rocks was evaluated in terms of their porosity and permeability characteristics [13].
- **Seal Rocks:** An investigation into the presence and integrity of seal rocks was conducted to ensure effective hydrocarbon trapping [14].

c. Well-log Interpretation

- **Correlation and Mapping:** Well logs from multiple wells were correlated to identify sand tops and create a coherent regional stratigraphic framework, utilizing a northwest-southeast orientation [15].
- **Synthetic Seismogram Generation:** Synthetic seismograms were created from density and sonic logs from the AYO-1 well to correlate well log data with seismic reflection data, allowing for a theoretical seismic response (Tsvankin, 2012).

d. Seismic Interpretation

- **Structural Interpretation**: Seismic sections were analyzed to define structural features, including faults and folds. This included generating:

o **Seismic Time Maps:** Maps illustrating the time taken for seismic waves to travel through different subsurface layers (Sheriff & Geldart, 1995).
o **Depth Maps:** Conversion of time maps to depth maps using velocity data for accurate representation of subsurface structures [16].
o **Fault Planes:** Mapping of fault planes to understand the distribution and orientation of fault systems [17].
o **Isochore Maps:** Maps showing the thickness of geological layers were produced to identify stratigraphic variations [18].

e. **Sequence Stratigraphy**

• **Galloway Sequence Model:** This model was applied to well-log data to identify and classify genetic sequences and system tracts. Key aspects included:
o **Reflection Amplitudes:** Variations in reflection strength were used to interpret lithological changes and depositional environments [19].
o **Reflection Geometry:** The shape and continuity of seismic reflections were analyzed to deduce sedimentary processes and sequence boundaries [20].
o **Continuity of Reflection:** The persistence of reflectors across seismic sections was used to define stratigraphic units and system tracts, as described by Prather et al.[21] and Anomneze et al. [22].

f. **Seismic Facies Analysis**

• **Identification of Facies:** Key seismic traverses were examined to identify distinct seismic facies representing various depositional environments and potential exploration plays (Wood et al., 1985).
• **Play Maps:** Maps depicting different play types were generated based on the analysis of seismic facies, assessing their hydrocarbon potential [23].

g. **Prospect Identification**

• **Petroleum Play Maps:** Seismic facies and play maps were integrated to locate potential sweet spots, leads, and prospects within the basin [24].
• **Volumetrics:** The volumes of hydrocarbons potentially present in the identified prospects were estimated using

methods like Monte Carlo simulations to assess uncertainties [25].

h. **Risk Assessment**

• **Exploration Risks:** A comprehensive evaluation of risks associated with drilling and exploring identified prospects was conducted, considering geological uncertainty, reservoir quality, and potential economic viability [26].

i. **Software and Tools**

• **Petrel Interpretation Software:** All geological and geophysical interpretations were performed using Petrel, a leading software for integrated reservoir modeling and interpretation. This software facilitated the integration and visualization of seismic, well log, and geological data [9].
• **Workstation:** Analyses were conducted at the Petroleum Geoscience Laboratory, Nnamdi Azikiwe University, Awka, which was equipped with the necessary software and computational resources for detailed geoscience analysis [27].

4. RESULTS AND DISCUSSION

4.1 Lithostratigraphic Correlation

The lithostratigraphic correlation was performed by flattening the formation tops on the top Albian. This method aligns the geological data to a consistent reference horizon, allowing for a clearer comparison and correlation of subsurface formations across different wells.

• **Formation Tops:** The flattening on top Albian facilitated the correlation of formation tops across the basin, revealing the extent and continuity of various lithostratigraphic units.
• **Extent of Rocks:** The well-log data indicated that source rocks, reservoir rocks, and seals are extensive throughout the basin. This finding is crucial as it suggests a widespread potential for hydrocarbon accumulation and trapping across the study area.
• **Source Rocks:** These rocks, identified through their organic content and maturity, are distributed broadly within the basin, implying that the basin has a robust potential for hydrocarbon generation.

- **Reservoir Rocks:** bThe reservoir rocks were found to be well-distributed, offering multiple potential targets for hydrocarbon exploration.
- **Seal Rocks:** The seals, consisting primarily of shale and other low-permeability rocks, were also extensive. Effective seals are vital for trapping hydrocarbons and preventing their migration from the reservoir.

Fig. 2 illustrates the distribution of these rock types, highlighting their spatial relationships and indicating areas with favourable conditions for hydrocarbon accumulation.

4.2 Sequence Stratigraphic Interpretation

The sequence stratigraphic analysis was carried out using the Depositional Sequence Model II, which helped in identifying and classifying sedimentary sequences within the well-log data.

- **Genetic Sequences:** Two distinct Genetic Sequences were identified in the sequence stratigraphy analysis. Each sequence represents a complete depositional cycle, encompassing a range of sedimentary environments and changes over time.
- **Sequence 1:** This sequence is characterized by specific depositional environments and sedimentological features observed in the well logs.
- **Sequence 2:** Another depositional cycle was identified, reflecting different sedimentary conditions and processes compared to Sequence 1.
- **Systems Tracts:** Each Genetic Sequence was further divided into Systems Tracts, which represent distinct stages in the depositional cycle. The following Systems Tracts were identified:
- **Lowstand Systems Tract (LST):** Associated with periods of low sea level, where sediment deposition typically occurs in fluvial or deltaic environments. The LSTs identified in the well logs are considered potential reservoirs due to their favourable conditions for reservoir rock development.
- **Transgressive Systems Tract (TST):** Formed during periods of rising sea level, characterized by the deposition of shales and fine-grained sediments. The TSTs in the study area are primarily composed of shales, which act as source rocks and seals in the petroleum system.

- **Highstand Systems Tract (HST):** Develops during high sea levels and is characterized by the deposition of sands and other reservoir-quality rocks. Shales within the HSTs serve as seals and contribute to the overall containment of hydrocarbons.

Fig. 3 illustrates the stratigraphic framework, highlighting the spatial distribution of the LSTs, TSTs, and HSTs, and showing their potential roles as reservoirs and seals.

4.3 Reservoir and Seal Potential

- **Potential Reservoirs:** The identified LSTs and HSTs were found to possess favourable characteristics for reservoir rocks, including good porosity and permeability. These intervals are promising targets for hydrocarbon exploration.
- **Source and Seal Units:** The shales within the TSTs and HSTs were determined to be effective source and seal units. These units are crucial for the generation and trapping of hydrocarbons, providing a complete petroleum system within the basin.

4.4 Implications for Exploration

The lithostratigraphic and sequence stratigraphic results provide a comprehensive understanding of the basin's petroleum system. The extensive distribution of source rocks, reservoir rocks, and seals across the basin suggests significant potential for hydrocarbon accumulation. The identified genetic sequences and systems tracts offer valuable insights into the sedimentary and structural framework of the basin, guiding future exploration and development efforts.

- **Exploration Targets**: The identified LSTs and HSTs present prime targets for drilling and exploration due to their favourable reservoir characteristics.
- **Resource Assessment**: The extensive seal units enhance the probability of successful hydrocarbon trapping, making the basin a promising candidate for further exploration and potential resource development.

The results of this study align with prior research conducted on the Basque-Cantabrian Basin, especially regarding the structural complexity and petroleum system elements. Earlier studies

have also highlighted the significance of salt diapirism in creating structural traps in this region. However, this work expands on those findings by providing a more detailed analysis of the halokinetic structures and their influence on reservoir development.

Previous studies focused primarily on seismic data without fully integrating well logs and petrophysical data. In contrast, our work combines multiple datasets, offering a more comprehensive understanding of the basin's evolution and the petroleum system. The identification of two genetic sequences with associated systems tracts further contributes to refining the regional stratigraphic framework, which was not as well-documented in earlier studies.

Additionally, while past research identified general potential for Jurassic plays, this manuscript goes a step further by conducting a quantitative resource assessment with volumetric calculations for the Lias Limestone and Carniolas Dolomite reservoirs.

By comparing the seismic facies observed here—such as the high-amplitude convergent (CBH) and low-amplitude convergent (CBHL) facies—with those documented in *[insert reference]*, it is clear that these facies are consistently associated with high reservoir quality, reinforcing the findings from earlier seismic facies analysis. However, the chaotic reflections observed in deeper sections in our study present new insights into the structural complexities that were not as evident in previous interpretations.

From the seismic to well Tie, It has a SEG Normal polarity zero phase seismic data. Ricker 35Hz wavelet, Good tie at well point and all Reservoirs top corresponds to Peaks.
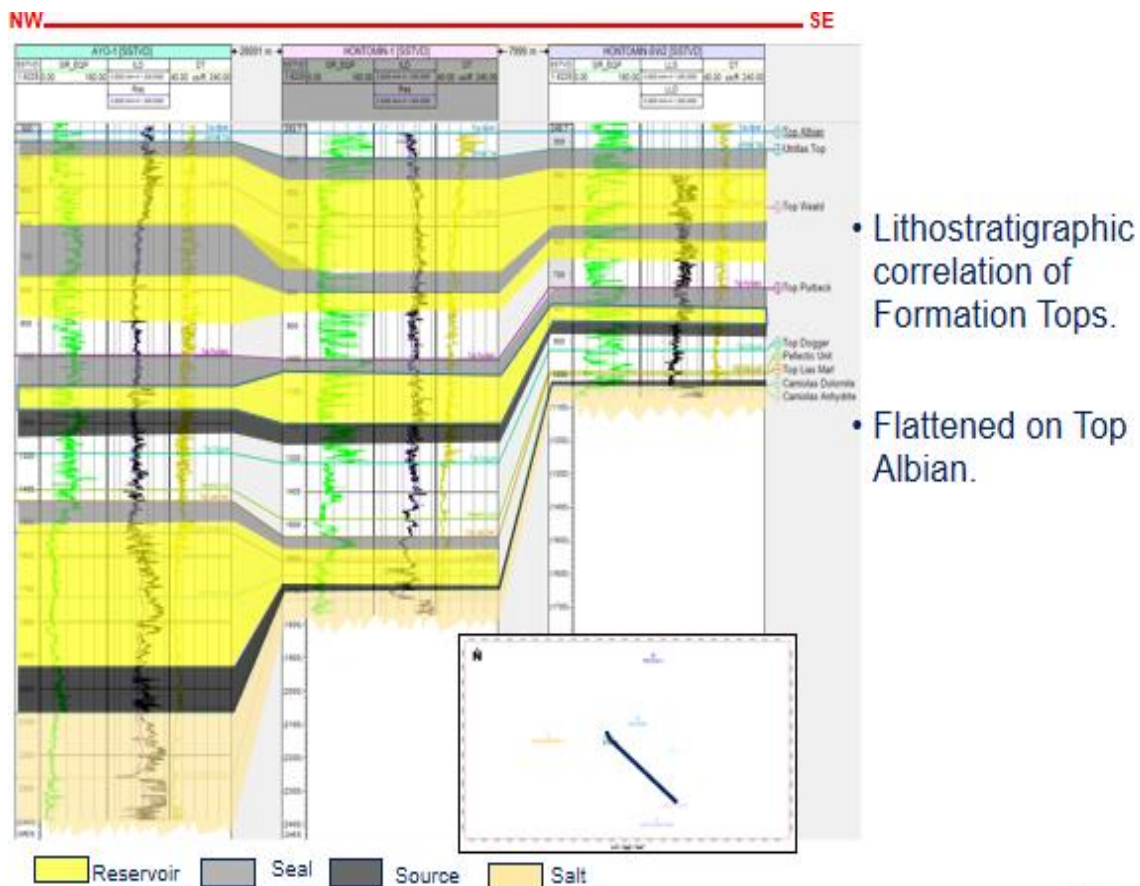

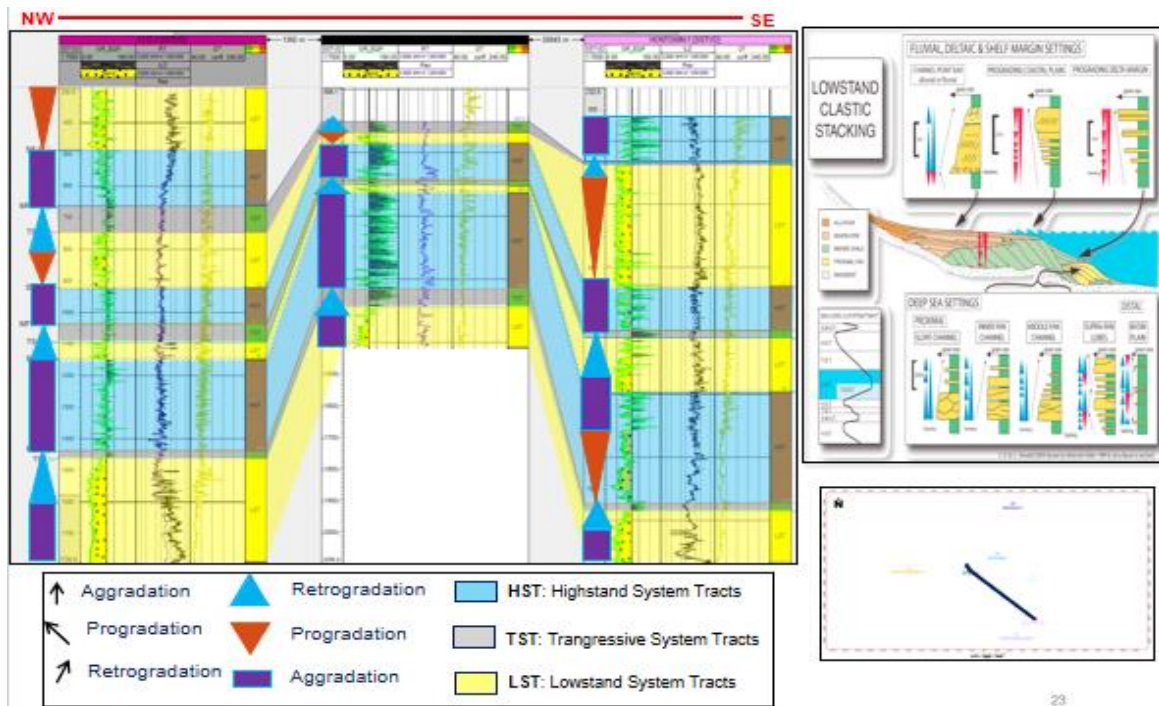**Fig. 2. Lithostratigraphic Correlation between Ayo-1, Ayo-35, and Hontomin-1 Wells**

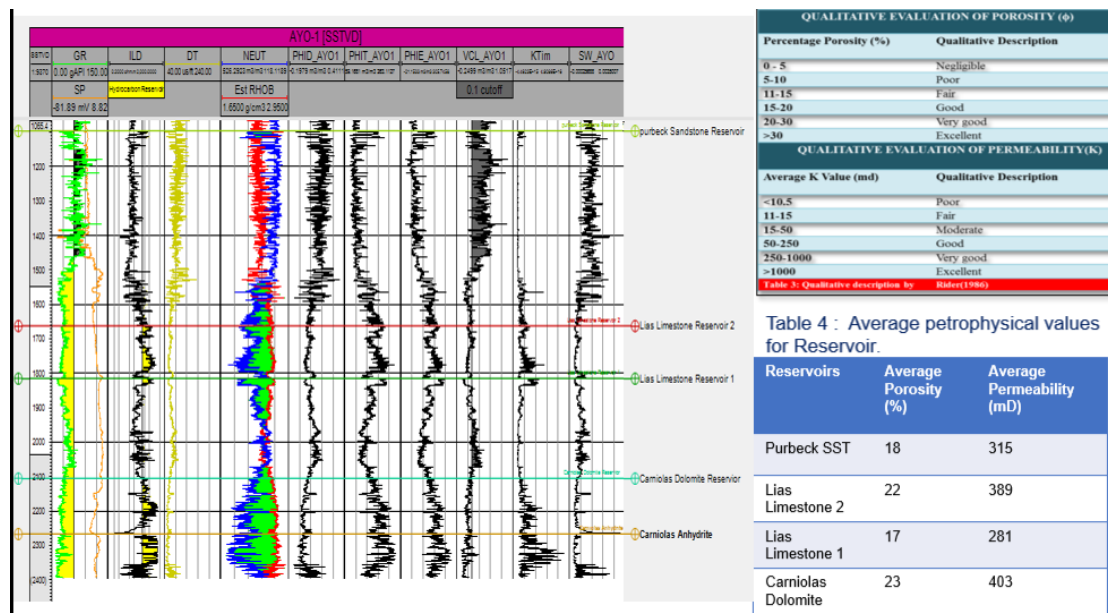**Fig. 3. Sequence Stratigraphic Interpretation using Depositional Sequence Model II**

Fig. 4. Ayo-1 well showing Petrophysical Logs

Four Reservoir were identify from the formation evaluation and are labelled Purbeck sandstone reservoir, Lias Limestone reservoir 1, Lias Limestone reservoir 2 and Carniolas Dolomite reservoir with average porosity and permeability of 18% & 315mD, 22% & 389mD, 17% & 281mD, and 23% & 403mD respectively (Fig. 4).

The identification and interpretation of these seismic facies provide valuable insights into the depositional environments and potential hydrocarbon-bearing zones within the Ayoluengo oil field. Each facies type offers distinct characteristics that are critical for understanding the spatial distribution of reservoir and seal rocks, as well as the overall petroleum system.

- **Fig. 7:** Illustrates the High-Amplitude Convergent (Cbh) and High- and Low-Amplitude Convergent (Cbhl) facies, showing their reflection patterns and potential implications for reservoir characterization.
- **Fig. 8:** Depicts the High- and Low-Amplitude Discontinuous, Shingled to Chaotic (Bhl) and Low-Amplitude

Convergent (Cbl) facies, highlighting the variability and complexity in sedimentary deposition.

The 'CBH' and 'CBHL' seismic facies shows the highest reservoir percentage and therefore ranked higher than other seismic facies identified. (Fig. 9).
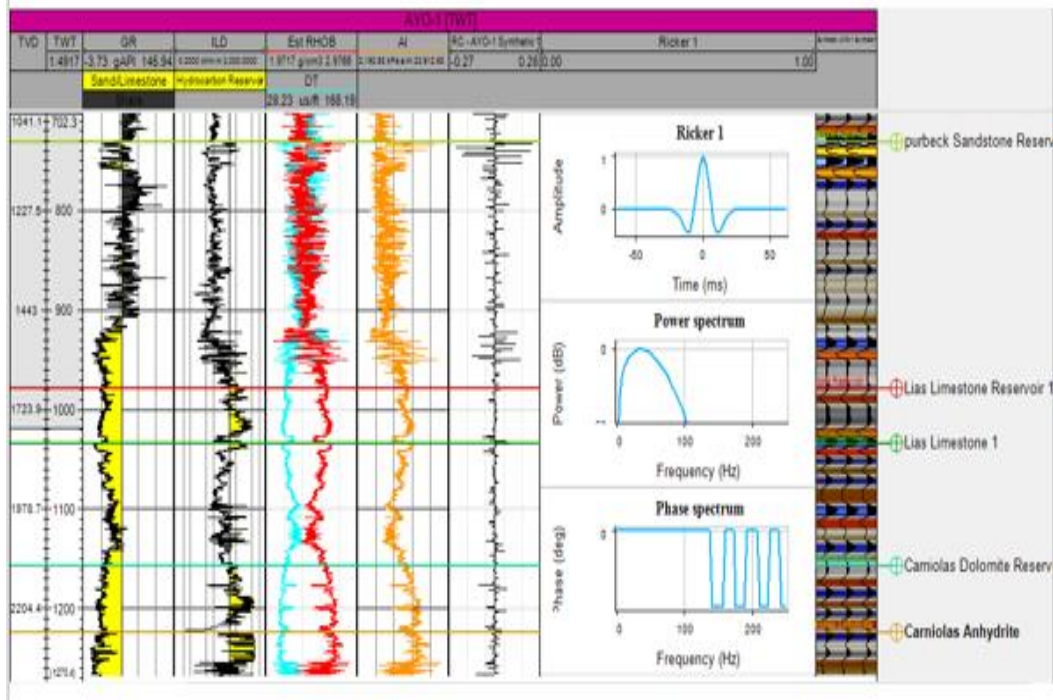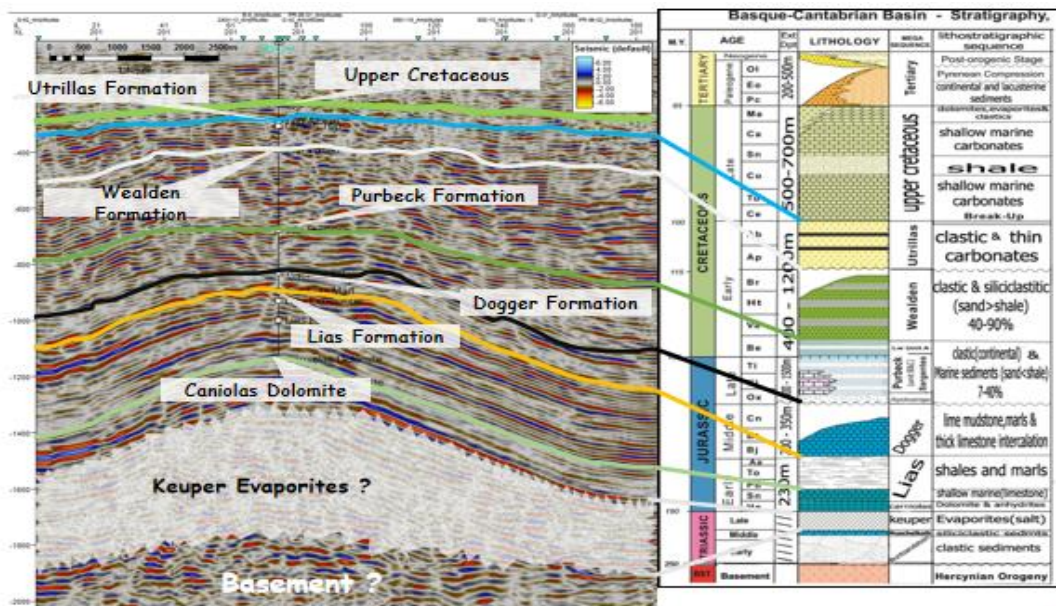

Fig. 5. Seismic to well tie using Ayo 1 well

Fig. 6. Interpretation of lithostratigraphic units with stratigraphic chart at Xline 201
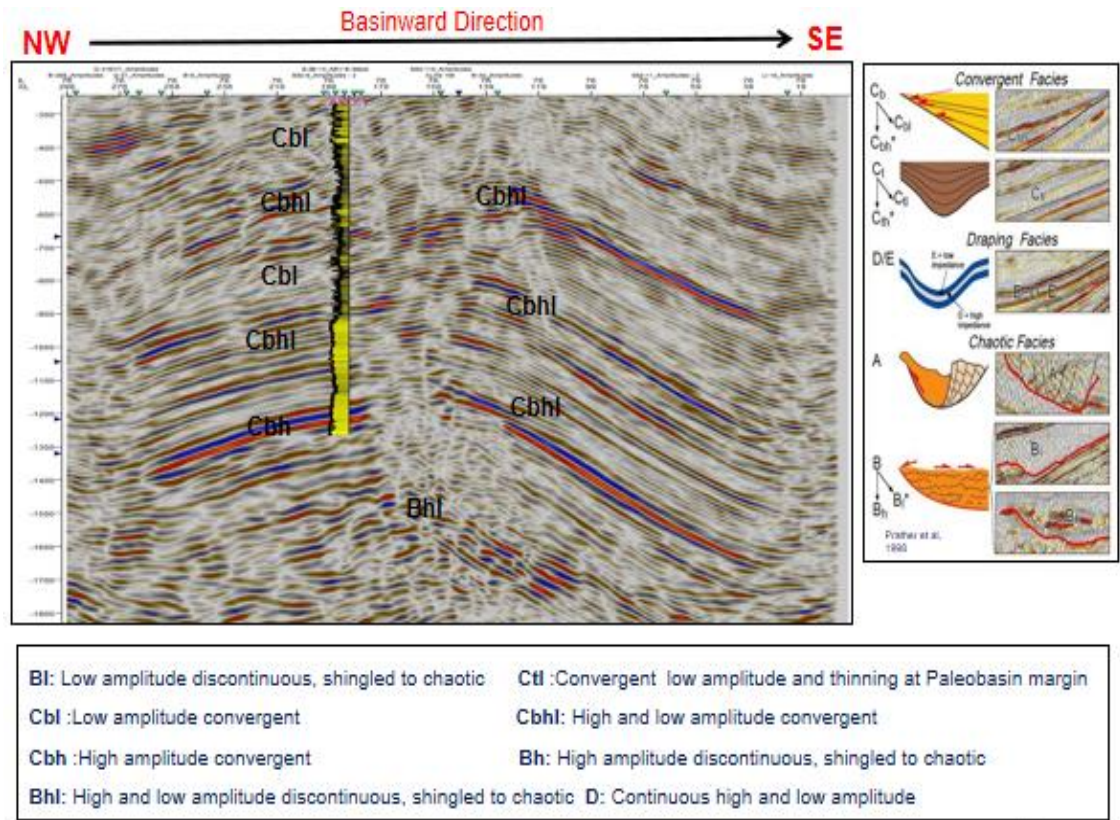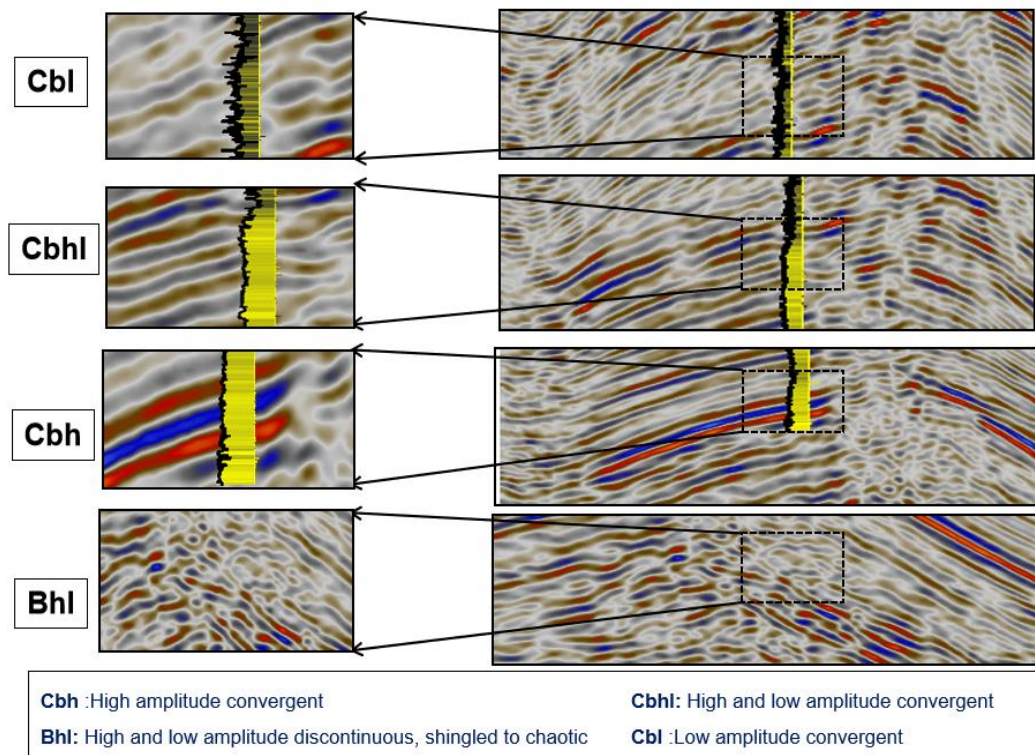
Fig. 7. Seismic facies analysis on seismic Dip Line 76

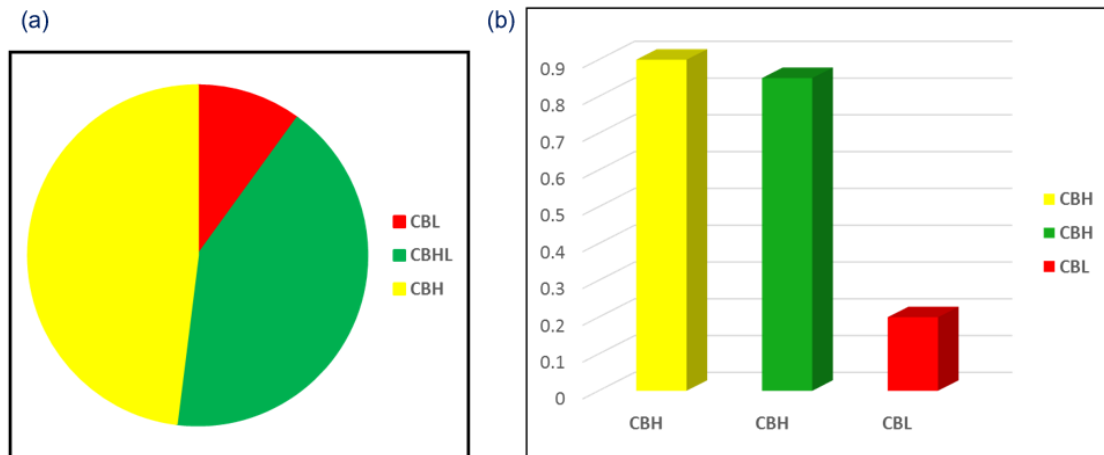**Fig. 8. Seismic facies interpretation (cont'd)**

Fig. 9. Reservoir percentage/ranking of seismic facies

In the seismic data interpretations, we observed the Presence of salt diapirs which is a Geologic feature, Reflections terminating against the upwelling feature and Chaotic reflections at deeper section.

1. **Presence of salt diapirs**

- **Description**: Salt diapirs are vertical or near-vertical intrusions of salt that pierce through overlying sedimentary layers. These diapirs result from the buoyant rise of salt due to its lower density compared to surrounding sediments. In the seismic data, salt diapirs are typically characterized by distinct high-amplitude reflections and a characteristic "domal" or "antiform" shape.
- **Seismic Signature**: Salt diapirs often appear as bright, high-amplitude reflections on seismic sections. They can create complex seismic patterns due to their irregular shape and the way they interact with surrounding sediments. The seismic signature includes:
  High-Amplitude Reflections: The diapirs themselves exhibit high-amplitude reflections due to the contrast in acoustic impedance between salt and the surrounding rock.
  Structural Distortion: The presence of diapirs can cause significant deformation in overlying and surrounding sedimentary layers. This often results in warping or tilting of reflections around the diapir, producing an anticline or dome-like structure on the seismic data.

- **Geological Implications**: Salt diapirs can influence petroleum exploration in several ways:
  Trapping Mechanisms: Diapirs can act as cap rocks, creating structural traps for hydrocarbons. They can also create complex trap configurations by folding or faulting the surrounding strata.
  Migration Pathways: The movement of salt can also influence fluid migration pathways, potentially affecting the distribution of hydrocarbons.
- **Figure**s: Seismic sections displaying salt diapirs often show these features as prominent, high-amplitude reflections with associated structural deformation in the surrounding strata.

2. **Reflections Terminating Against Upwelling Features**

- **Description**: Reflections that terminate against upwelling features indicate geological structures where sedimentary layers have been interrupted or displaced due to an upwelling or intrusions, such as salt diapirs, magma bodies, or tectonic activity.
- **Seismic Signature**: On seismic data, these features are observed as abrupt terminations or terminations of reflections at the boundaries of the upwelling feature. The seismic signature includes:
  Termination of Reflections: Reflections may abruptly end or show significant disruption where they intersect the upwelling feature, reflecting the

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discontinuity or disturbance in sedimentary layering.

Distortion Patterns: Reflections might be bent, warped, or offset as they approach the upwelling feature, indicating structural deformation.

- **Geological Implications**:

Structural Analysis: The termination of reflections provides insight into the shape and extent of the upwelling feature and its impact on the surrounding sedimentary layers.

Exploration Considerations: Understanding where and how these features disrupt reflections can be critical for identifying potential hydrocarbon traps or areas of significant geological interest.

- **Figures**: Seismic images showing reflections terminating against upwelling features often reveal clear boundaries or disruptions in the continuity of reflections, illustrating the influence of the upwelling on the surrounding geology.

3. Chaotic Reflections at Deeper Sections

- **Description**: Chaotic reflections in deeper seismic sections are characterized by irregular, non-uniform, and disorganized seismic patterns. These chaotic reflections typically occur in deeper sedimentary layers and can indicate complex subsurface conditions.

- **Seismic Signature**: Chaotic reflections appear as scattered, high-amplitude, and low-amplitude reflections with no clear, continuous pattern. The seismic signature includes:

Irregular Reflection Patterns: Reflections may appear disordered, with varying amplitudes and irregular geometry.

Lack of Continuity: Unlike well-defined, continuous reflections, chaotic reflections lack a consistent pattern and do not correlate well with other seismic features.

- **Geological Implications**:

Sedimentological Interpretation: Chaotic reflections can be indicative of complex depositional environments or structural disturbances, such as those associated with deep-seated salt movements or tectonic activity.

Exploration Challenges: The presence of chaotic reflections can complicate the interpretation of subsurface geology and make it challenging to delineate potential reservoirs or traps.
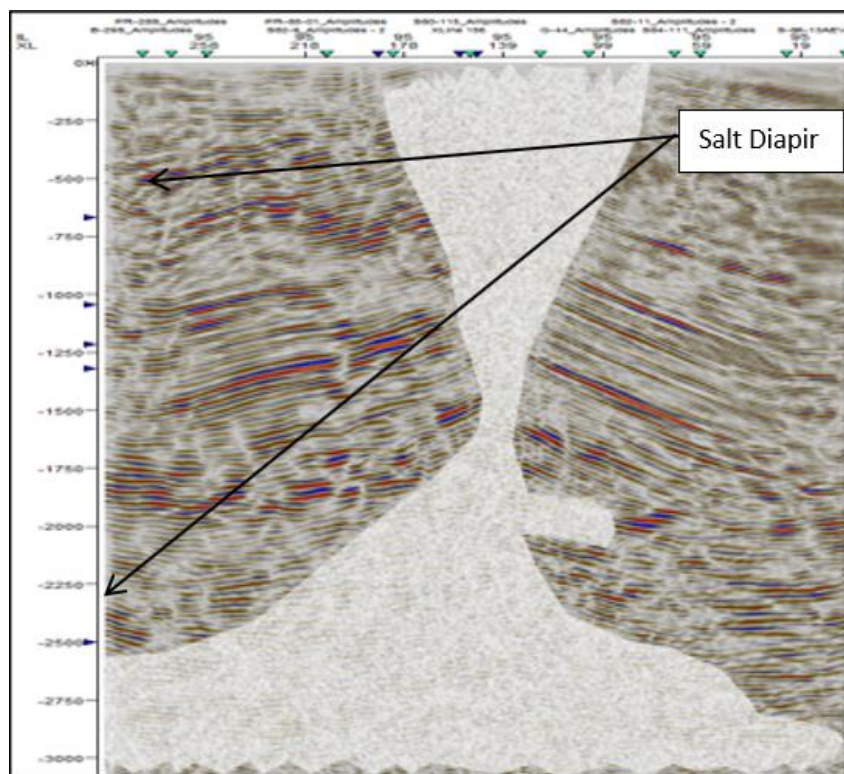

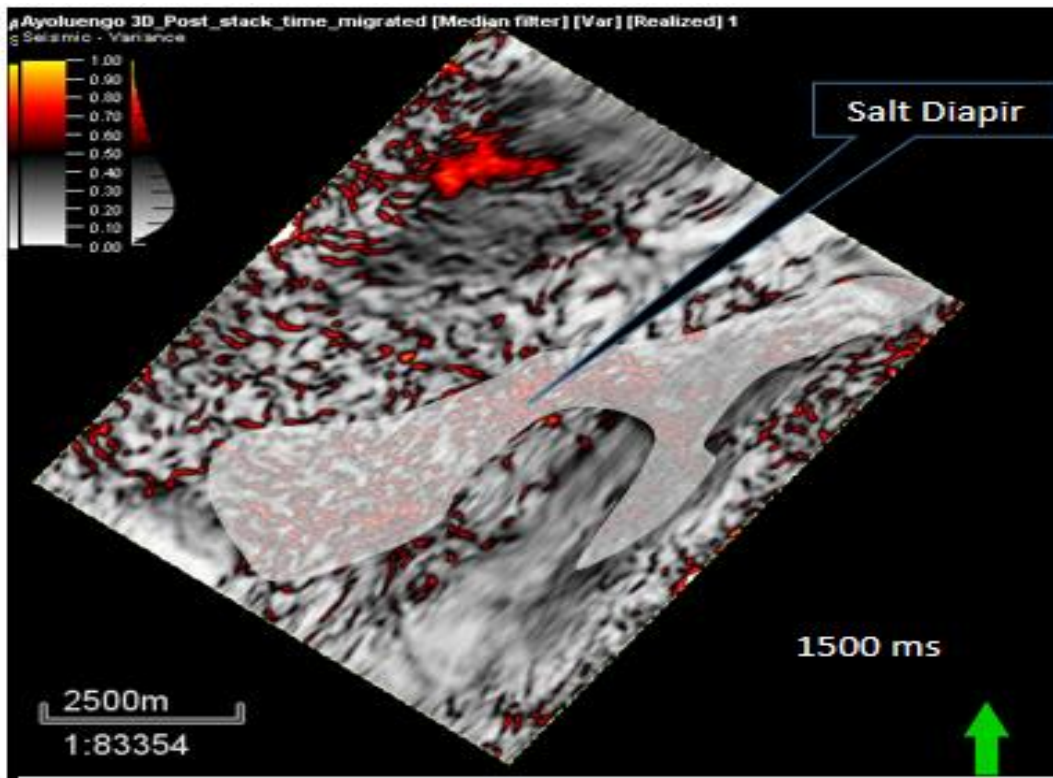**Fig. 10. Seismic dip line 95 showing Geologic features**

Fig. 11. Development of salt diapir analyzed using variance slices at 900ms, 1184ms, and 1500ms
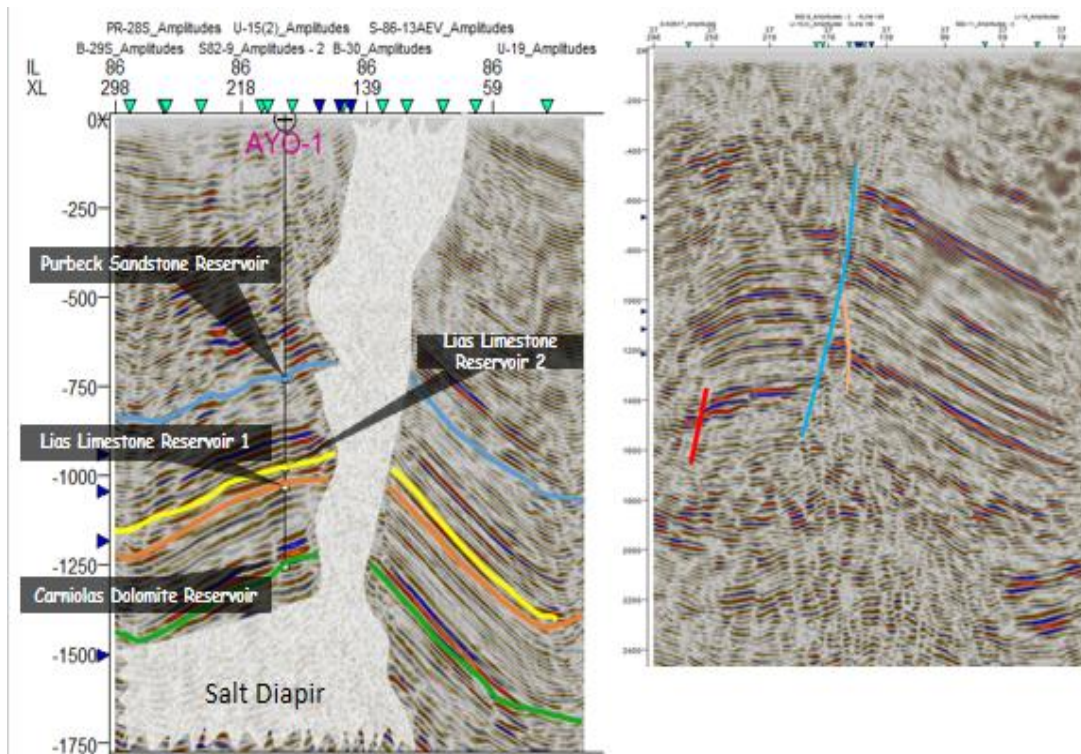

Fig. 12. Seismic dip line showing interpreted (a) Horizons and (b) faults

In the Development of salt diapir which was analyzed using variance slices at 900ms, 1184ms, and 1500ms, we observed that faults are not prominent but fractures are present, the presence of Halokinetic structures and folded structures due to salt diapiris.

The structural framework interpretation indicates the presence of minor and major normal faults, which play essential roles in migration pathways and hydrocarbon traps. Halokinetic structures and folded structures are also present. The presence of salt diapirs, which is the main structural feature. Four reservoirs were mapped in total. The reservoirs terminate against the salt diapir (Fig. 12).
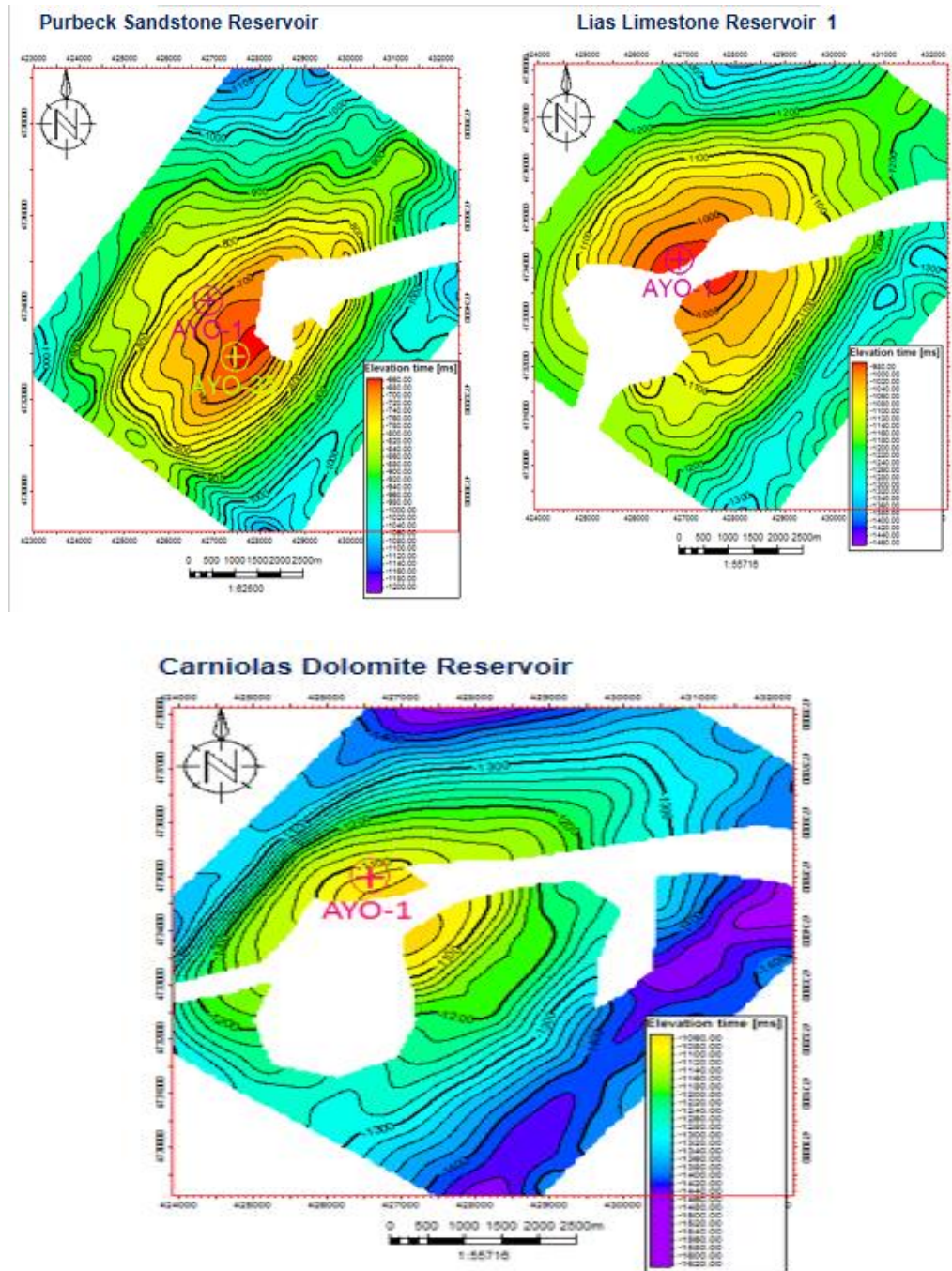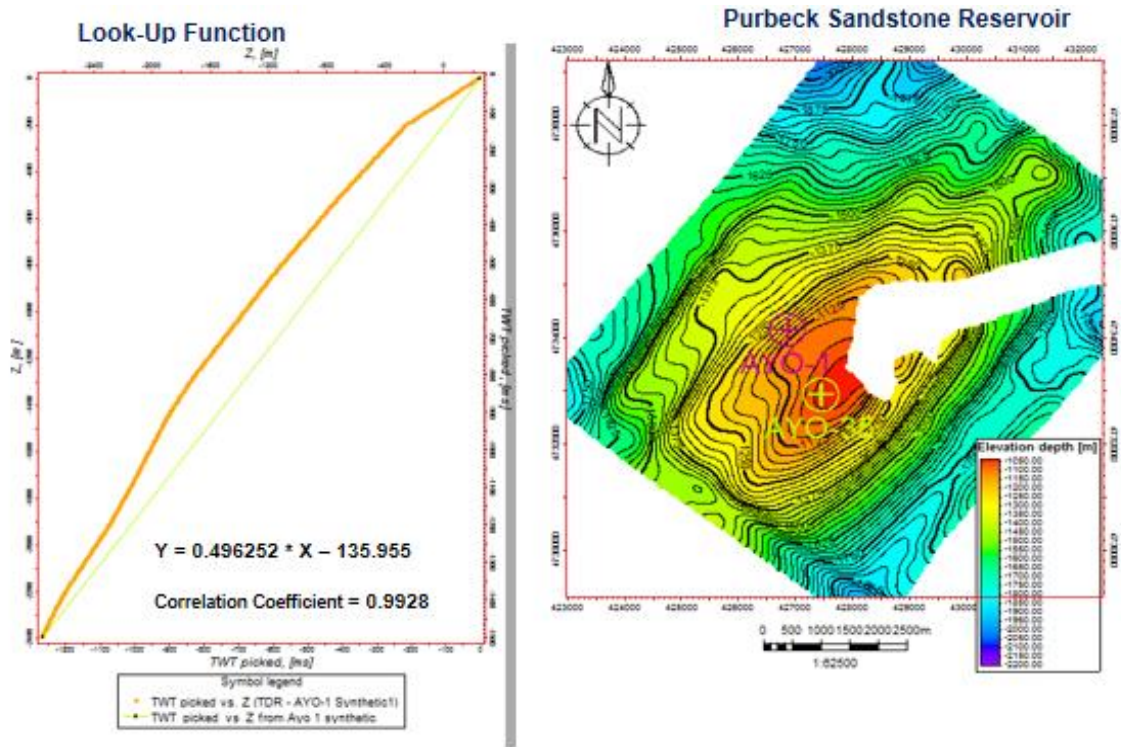

Fig. 13. Surfaces generated in Time domain

Fig. 14. a). Look-up function from checkshot data. B). Depth surface map of purbeck sandstone reservoir
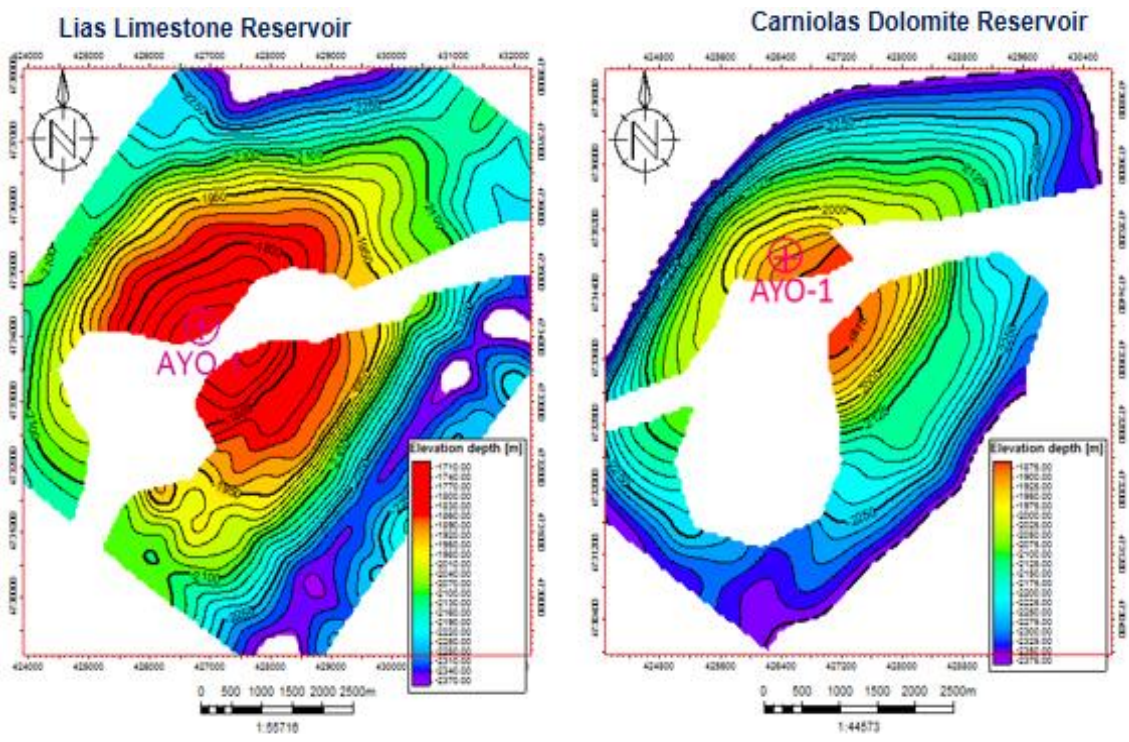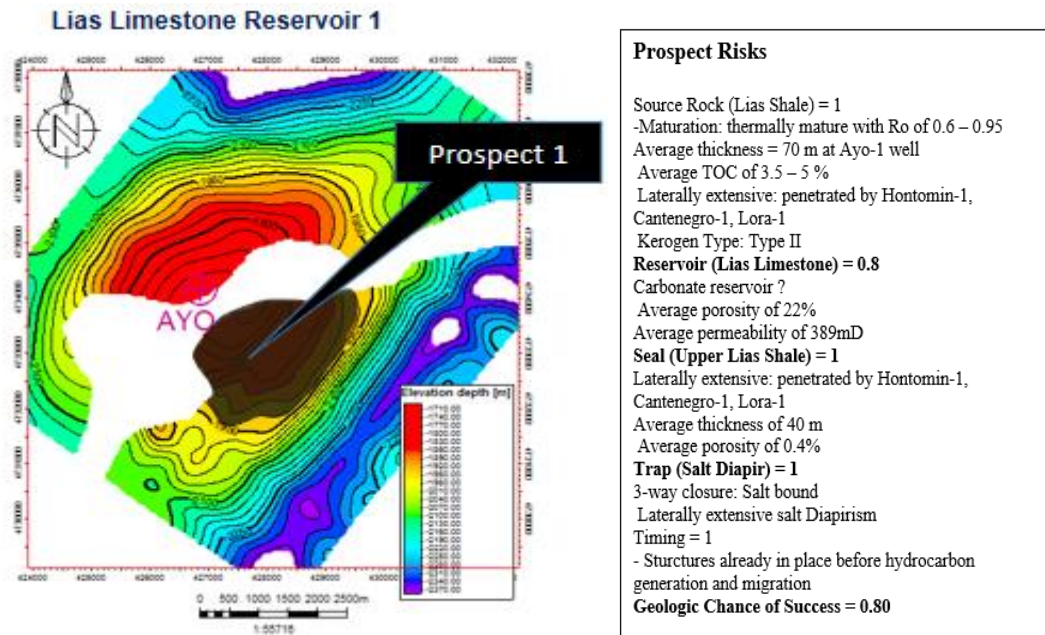

Fig. 15. Surfaces generated in depth domain

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Lias Limestone Reservoir 1

Prospect Risks

Source Rock (Lias Shale) = 1
-Maturation: thermally mature with Ro of 0.6 – 0.95
Average thickness = 70 m at Ayo-1 well
 Average TOC of 3.5 – 5 %
 Laterally extensive: penetrated by Hontomin-1,
Cantenegro-1, Lora-1
 Kerogen Type: Type II
Reservoir (Lias Limestone) = 0.8
Carbonate reservoir ?
 Average porosity of 22%
Average permeability of 389mD
Seal (Upper Lias Shale) = 1
Laterally extensive: penetrated by Hontomin-1,
Cantenegro-1, Lora-1
Average thickness of 40 m
 Average porosity of 0.4%
Trap (Salt Diapir) = 1
3-way closure: Salt bound
 Laterally extensive salt Diapirism
Timing = 1
- Sturctures already in place before hydrocarbon
generation and migration
Geologic Chance of Success = 0.80

Fig. 16. Prospect identification for Lias Reservoir 1

Carniolas Dolomite Reservoir

Prospect Risks

Source Rock (Lias Shale) = 1
-Maturation: thermally mature with Ro of 0.6 –
0.95
Average thickness = 70 m at Ayo-1 well
 Average TOC of 3.5 – 5 %
 Laterally extensive: penetrated by Hontomin-1,
Cantenegro-1, Lora-1
 Kerogen Type: Type II
Reservoir (Carniolas Dolomite) = 0.85
Carbonate reservoir ?
 Average porosity of 23%
Average permeability of 403mD
Seal (Lias Shale) = 1
Laterally extensive: penetrated by Hontomin-1,
Cantenegro-1, Lora-1
Average thickness of 70 m at Ayo-1 well
 Average porosity of 2%
Trap (Salt Diapir) = 1
3-way closure: Salt bound
 Laterally extensive salt Diapirism
Timing = 1
- Structures already in place before hydrocarbon
generation and migration
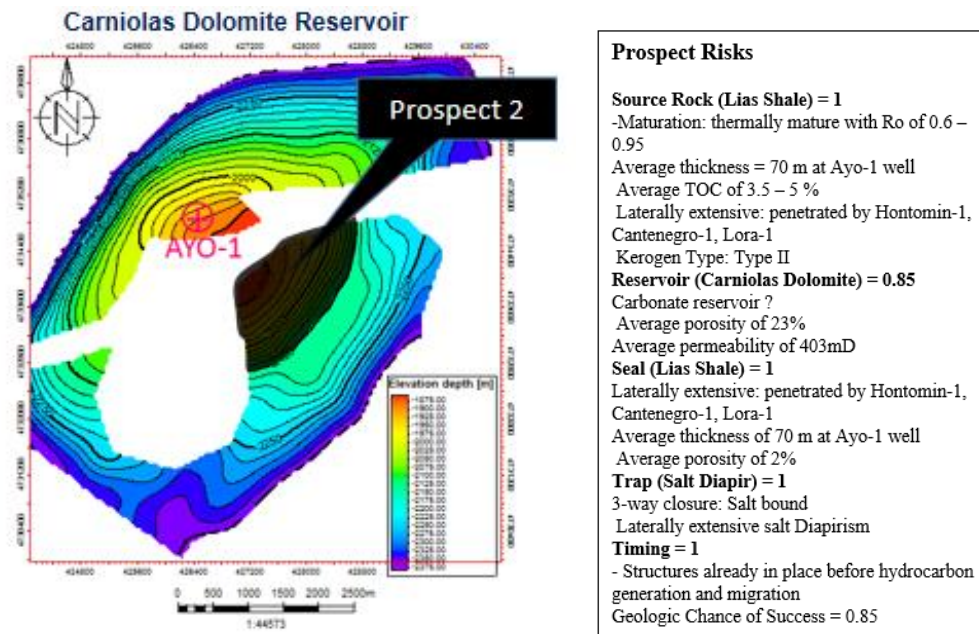Geologic Chance of Success = 0.85

Fig. 17. Prospect identification for carniolas dolomite reservoir

Table 1. Calculation of volumetrics for reservoir 1: Lias limestone

Reservoir: Lias Limestone	P90	P50	P10
	7758	7758	7758
Area (m2)	4.1 * 10^6	4.6 * 10^6	5.1 * 10^6
H (m)	65.38	72.65	79.92
Porosity (%)	19.8	22	24.2
Hydrocarbon Saturation	0.9	1.0	1.1
Formation Volume Factor	1.35	1.5	1.65
STOIIP (Bbbl)	3.4*10^16	3.8 *10^16	4.2*10^16

Table 2. Calculation of volumetrics for reservoir 2: carniolas dolomite

Reservoir: Carniolas Dolomite	P90	P50	P10
	7758	7758	7758
Area (m2)	$1.1 * 10^6$	$1.2 * 10^6$	$1.3 * 10^6$
H (m)	142.77	158.63	174.49
Porosity (%)	21	23	25
Hydrocarbon Saturation	0.57	0.63	0.69
Formation Volume Factor	1.35	1.5	1.65
STOIIP (Bbbl)	$1.26*10^{16}$	$1.4*10^{16}$	$1.56*10^{16}$

5. CONCLUSION

Integration of multiple datasets resulted in the identification of one Plays, and two prospect. Jurassic Play, Lias Limestone Prospect with 80% Geologic Chance of Success, and Carniolas Dolomite with 85% Geologic Chance of Success. Four reservoirs, one major source rock, two regional seal & inter-reservoir seals, laterally extensive salt diapirs acting as traps have been identified. Two Genetic Sequences were identified with their associated Systems Tracts. The LSTs and HSTs are potential reservoirs, the shales of TSTs and HSTs constitute the source/seal units. There were uncertainties in well correlation due to wells located far apart with the closest at 1.3km (Ayo-1 and Ayo-35). The seismic data quality was poor seismic data quality (2D characterized mostly by noise and artifacts). There were uncertainties in depth conversion due to shallow wells. Shallow wells drilled with the deepest at 2397m. The implementation of these will significantly maximize the hydrocarbon potential of the Ayoluengo oil field in the Basque-Cantabrian basin in Spain.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Martínez del Olmo W. The ayoluengo and hontomín fields: The first Spanish oil and gas discoveries. Boletín Geológico y Minero. 2019;130(2), 231-256.

2. García-Mondéjar J, Fernández-Mendiola PA, Agirrezabala LM. Plate reconstruction of the Bay of Biscay. Geology. 1996;24(7):635-638.

3. Álvarez de Buergo E, García R. Ayoluengo field-Spain, Basque-Cantabrian Basin. In AAPG treatise of petroleum geology, Atlas of oil and gas fields, structural traps VII. American Association of Petroleum Geologists. 1996;29-48.

4. Tavani S. Plate kinematics in the cantabrian domain of the pyrenean orogen. Solid Earth. 2012;3(2), 265–292. Available:https://doi.org/10.5194/se-3-265-2012

5. Quintà A, Tavani S. The foreland deformation in the southwestern Basque-Cantabrian Belt (Spain). Tectonophysics. 2012;576:4-19. Available:https://doi.org/10.1016/j.tecto.2012.02.015

6. Hernáiz Huerta PP, Solé Pont J. Las estructuras del diapiro de Salinas de Rosío y del alto de San Pedro-Iglesias y sus implicaciones en la evolución tectónica de la transversal burgalesa de la Cordillera Vascocantábrica-Cuenca del Duero. Revista de la Sociedad Geológica de España. 2000;13(3-4):471-486.

7. Carola E, Tavani S, Ferrer O, Granado P, Quintà A. Salt tectonics and controls on halokinetic-sequence geometry in the Basque-Cantabrian Basin, northern Spain. Journal of Structural Geology. 2015;73:1-17. Available:https://doi.org/10.1016/j.jsg.2015.01.009

8. Permanyer A, Márquez G, Gallego JR. Compositional variability in oils and formation waters from the ayoluengo and hontomín fields (Burgos, Spain). Implications for assessing biodegradation and reservoir compartmentalization. Organic Geochemistry. 2013;54:125 -139. Available:https://doi.org/10.1016/j.orggeochem.2012.10.007

9. Schlumberger. Well log interpretation. Schlumberger Oilfield Glossary. Retrieved from [Schl; 2010.
10. Blum MD, Tye RS. Sequence stratigraphy and paleogeography of the Upper Cretaceous. Journal of Sedimentary Research. 2004;74(4):568-580.
11. Hunt JM. Petroleum geochemistry and geology. W.H. Freeman and Company; 1996.
12. Baldwin EM. Hydrocarbon migration pathways in sedimentary basins. AAPG Bulletin. 1990;74(1): 24-45.
13. Aasly K, Hurst A, Michie R. Porosity and permeability of reservoir rocks: A comprehensive review. Journal of Petroleum Science and Engineering. 2011;78(3), 368-379.
14. Peters KE. The role of seal rocks in hydrocarbon entrapment. Petroleum Geoscience. 2007;13(2): 119-130.
15. Luthi SM. Well Logging Principles and Applications. Elsevier Science; 2001.
16. Bourlès DL. Time-to-depth conversion in seismic data interpretation. Geophysics. 2003;68(3): 1113-1122.
17. Childs C. Structural analysis and interpretation of faults in seismic data. Petroleum Geoscience. 2007;13(3):237-248.
18. Hudson JA. Estimation of geologic thickness using isochore maps. Geological Society of America Bulletin. 1993;105(10):1327-1334.
19. Galloway WE. Genetic stratigraphic sequences in basin analysis: Conceptual framework and stratigraphic practice. AAPG Bulletin. 1989;73(2):125-142.
20. Mitchum RM. Stratigraphic interpretation of seismic reflection data. AAPG Bulletin. 1977;61(5): 983-994.
21. Prather BE, Booth JR, Steffens GS, Craig PA. Classification, lithologic calibration, and stratigraphic succession of seismic facies of intraslope basins, deep-water Gulf of Mexico. AAPG Bulletin. 1998;82(5):701-728.
    Available:https://doi.org/10.1306/1D9BC5D9-172D-11D7-8645000102C1865D
22. Anomneze AJ. Application of seismic stratigraphy in the interpretation of a hydrocarbon reservoir. Nigerian Journal of Petroleum Science. 2015;6(2):17-30.
23. Santos CR. Seismic facies analysis for hydrocarbon exploration. Journal of Petroleum Science and Engineering. 2014;113:204-213.
24. Hassan MM. Play-based exploration: Integrating seismic and geological data. Journal of Natural Gas Science and Engineering. 2017;41:66-75.
25. Raghavan R. Uncertainty analysis in hydrocarbon volumetric estimation using Monte Carlo simulation. Journal of Petroleum Science and Engineering. 2004; 43(1):13-26.
26. Meyer R. Assessment of exploration risk in petroleum systems. Journal of Petroleum Exploration and Production Technology. 2015;5(1):1-9.
27. Anomneze DO, Okoro AU, Ajaegwu NE, Akpunonu EO, Ahaneku CV, Ede TA, Chiadikobi KC, Chiaghanam OI. Application of seismic stratigraphy and structural analysis in the determination of petroleum plays within the eastern Niger Delta Basin, Nigeria. Journal of Petroleum Exploration and Production Technology. 2015;5(2):113-122.
    Available:https://doi.org/10.1007/s13202-015-0161-2